Journal of Cleaner Production 208 (2019) 261–273

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Emissions of air pollutants from primary crop residue burning in India and their mitigation strategies for cleaner emissions

Khaiwal Ravindra [a, *], Tanbir Singh [b], Suman Mor [b]

[a] School of Public Health, Department of Community Medicine, Post Graduate Institute of Medical Education and Research (PGIMER), Chandigarh, 160012, India

[b] Department of Environment Studies, Panjab University, Chandigarh, 160014, India

ARTICLE INFO

Article history:
Received 18 May 2018
Received in revised form
3 October 2018
Accepted 4 October 2018
Available online 5 October 2018

Keywords:
Crop residue burning
Emission trends
Emission inventory
Technological & non-technological mitigation
Co-benefits
Clean development mechanism

ABSTRACT

Population growth will lead to an increase in food demand, which will exert pressure on crop production and likely increase the agricultural crop residue. The present study estimates atmospheric emissions of various pollutants from crop residue burning using the Intergovernmental Panel on Climate Change guidelines. In India 488 Mt of total crop residue was generated during 2017, and about 24% of it was burnt in agricultural fields. This resulted in emissions of 824 Gg of Particulate Matter ($PM_{2.5}$), 58 Gg of Elemental Carbon (EC) and 239 Gg of Organic Carbon (OC). Additionally, 211 Tg of CO_2 equivalent greenhouse gases (CO_2, CH_4, N_2O) were also added to the atmosphere. However, crop residue can also be used for energy production in biomass power plants and has the potential of 120 TWh of electricity generation. This accounts for 10% of the total energy production of India. Trend analysis in a Business As Usual (BAU) model shows that crop residue burning emissions will increase by 45% in 2050 having 2017 as the base year. The study also examines the various sustainable approaches and proposes an integrated crop residue management model to minimize the adverse impact of agricultural waste burning on human health and the environment.

© 2018 Elsevier Ltd. All rights reserved.

1. Introduction

Biomass burning is one of the major contributors to air pollution other than industrial and vehicular emissions (Gurjar et al., 2016). Akagi et al. (2011) reported biomass burning as the largest source of primary fine carbonaceous particles, whereas it remains the second largest source of trace gases in the troposphere. In Asia, around 730 Tg of biomass is burned annually from both natural and anthropogenic sources which include forest fires, grassland fires, and crop residue burning in the field, of which 18% is contributed by India (Streets et al., 2003a, b). Venkataraman et al. (2006) estimated that around 18–30% of crop residue is burned in agricultural fields. A study by Jain et al. (2014) also found that ~15.9% residue is burned in agricultural fields in India. In-situ crop residue burning is practiced not only in India but also worldwide (McCarty et al., 2009; Chen et al., 2017) despite having detrimental effects on air quality and human health.

Burning of crop residue in agricultural fields leads to the emissions of various air pollutants including Greenhouse gases (GHGs), which can play an important role in changing the atmospheric chemistry locally, regionally and globally (Bencs et al., 2008, 2010; Ravindra et al., 2016a). Many developed countries have banned the burning of agricultural residue. However, it is still a prevailing practice in developing countries due to poor crop residue management. Preparation of fields for next season's crop, weeds removal, nutrient regeneration in croplands and to control agricultural diseases and pests are some of the major reasons mentioned to burn crop residues (Crutzen and Andreae, 1990; Gadde et al., 2009a).

The amount of crop residue burned in fields has large regional variations and mainly depends on the crop type. The uncontrolled burning of crop residue leads to atmospheric emissions of various pollutants such as Particulate matter (PM_{10}, $PM_{2.5}$), Carbon monoxide (CO), Carbon dioxide (CO_2), Sulphur dioxide (SO_2), Oxides of nitrogen (NO_x), Ammonia (NH_3), Methane (CH_4), Elemental Carbon (EC), Organic Carbon (OC), Volatile Organic Compounds (VOCs), Polycyclic Aromatic Hydrocarbons (PAHs) as reported by Awasthi et al. (2011); Jain et al. (2014) for India; Zhang et al. (2018) for

* Corresponding author.
E-mail addresses: khaiwal@yahoo.com, Khaiwal.Ravindra@pgimer.edu.in (K. Ravindra).

https://doi.org/10.1016/j.jclepro.2018.10.031
0959-6526/© 2018 Elsevier Ltd. All rights reserved.

China and Oanh et al. (2018) for south-east Asia. Emissions of pollutants and their dispersion varies according to seasons, meteorology and type of agricultural residue (Kaskaoutis et al., 2014; Sen et al., 2017). The crop residue burning emissions also play a significant role in cloud microphysics, radiation balance and atmospheric chemistry in the lower atmosphere. This could potentially affect biogeochemical cycles and climate as suggested by Ramanathan et al. (2005); McNeill (2017).

The declining air quality due to crop residue burning in the rural areas and its dispersion in surrounding areas are of great concern due to its adverse impacts on human health and the environment (Awasthi et al., 2011; Ravindra et al., 2016a). However, to better understand the associated health risks, explicitly designed epidemiological studies are needed (Awasthi et al., 2017). Agarwal et al. (2010) and Awasthi et al. (2010) reported that not only long-term but also short-term exposure to crop residue burning causes respiratory disorders. These studies also highlight that vulnerable populations, such as children, are at higher risk. Hence, atmospheric emissions from crop residue burning pose a serious threat to human health (Chandra and Sinha, 2016) and there is a need to minimize these emissions.

Technological development in the agricultural sector and use of modern agricultural practices like combine harvesters have increased the production of crop residue. It is estimated that 10^9 ha of natural ecosystems will be converted to agriculture land by 2050 (Tilman et al., 2001). A report from the United Nations Department of Economic and Social Affairs estimated that the world population will be 9.7 billion by 2050. This will exert pressure on the agriculture sector to meet their needs, particularly in South Asia (UN DESA, 2015).

An increase in crop production will also lead to the generation of additional crop residue. Hence, there is a need to identify sustainable crop residue management practices. Further, an accurate country-specific emission inventory is required for better air quality management. Hence, this study estimated the atmospheric emissions from crop residue burning using the Intergovernmental Panel on Climate Change (IPCC) guidelines. Further, having 2017 as a base year, crop residue burning emissions were also modeled up to 2050. These estimates of crop residue burning will be useful for air quality models to support air quality management and for policymakers to better plan mitigation strategies. The study also assesses the existing alternative practices for utilization of crop residue and proposes an integrated model for sustainable crop residue management.

2. Methodology

A comprehensive national inventory of crop residue burning emissions including various air pollutants and greenhouse gases such as $PM_{2.5}$, PM_{10}, CO, CO_2, SO_2, NOx, N_2O, NH_3, CH_4, Non-methane VOCs (NMVOC), EC, OC, PAH was prepared using IPCC, 2006 guidelines. The data of annual crop production were acquired from the Department of Agriculture, Cooperation, and Farmers Welfare, India (http://agricoop.nic.in/) for the financial year 2003–04 to 2016–17 and projections were made for crop residue generation upto 2050. The projections data were taken from the Food and Agricultural Organisation (Alexandratos and Bruinsma, 2012), which estimates there will be an annual growth of 1.5 percent per annum for all crops until 2030 and after that crop production growth will decline to 0.9 percent per annum (2030–2050) in India (Alexandratos and Bruinsma, 2012).

Traditionally, dual cropping systems are followed in India including *rabi* and *kharif* crops. *Rabi* crops are winter crops, which are sown in October–December. The *kharif* crops are the monsoon crops and they are sown in months of May–July. The main crops considered for the atmospheric emission inventories include rice, wheat, coarse cereals, total pulses, sugarcane, total nine oilseeds, cotton, jute & mesta. The coarse cereals include sorghum (jowar), pearl millet (bajra), maize, finger millet (ragi) and barley, whereas total pulses include pigeon pea (tur), gram, split black gram (urad), split green gram (moong), and other *rabi* and *kharif* pulses. The total nine oilseeds crop consists of groundnut, castor seed, sesamum, niger seed, rapeseed and mustard, linseed, safflower, sunflower, soybean were considered for the atmospheric emission inventory.

The total amount of atmospheric emissions of various pollutants from the burning of different crop residues was calculated using equation (1) (IPCC, 2006)

$$E(Gg/yr) = TCRB \times EF \quad (1)$$

Where

E = total emissions of the species in Gg
TCRB = total mass of crop residue burned in situ in Mt
EF = crop specific emission factor in g kg^{-1}

The total crop residue generated was calculated using crop-specific production to residue ratio and dry matter to crop ratio as calculated by Jain et al. (2014). The total mass of crop residue burned in the fields was calculated using equation (2) as applied by Streets et al. (2003a).

$$TCRB\ (Mt) = \Sigma_{crops}\ (P \times R \times D \times E \times B) \quad (2)$$

where

TCRB = total mass of crop residue burned in-situ (Mt)
P = crop production during the specific year
R = crop-specific production to residue ratio
D = dry matter to crop ratio
E = burning efficiency
B = percentage of dry matter residue burned in fields (%)

The coefficients of various parameters used in the calculation of crop residue burning emission inventory are mentioned in Table 1. As there is no comprehensive study available on different parameters such as dry matter to crop ratio, production to residue ratio, dry matter burned in fields and burning efficiency. Hence, these parameters were calculated from various studies as mentioned in Table 1. As all coefficients for all coarse cereals and pulses were not available, the value of maize was taken as the representative for coarse cereals and soybean for total pulses.

The estimation of greenhouse gases as CO_2 equivalent emissions (CO_2e) in Gigagram (Gg) was calculated using equation (3) while considering Global Warming Potential (GWP) for CH_4 and N_2O as 25 and 298 respectively (Gadde et al., 2009b).

$$E_{GHG} = E_{CO2} + E_{CH4} \times GWP_{CH4} + E_{N2O} \times GWP_{N2O} \quad (3)$$

where

E_{GHG} = emission of total CO_2 equivalent emissions GHG emissions
E_{CH4} and E_{N2O} = emission of CH_4 and N_2O
GWP_{CH4} & GWP_{N2O} = Global Warming Potential of CH_4 and N_2O

The Theoretical Energy Potential (TEP) was estimated using equation (4). It is the product of Lower Heating Value (LHV) of each crop and the amount of residue generated correspondingly.

Table 1
Type of crops and coefficients used for the preparation of crop residue burning emission inventory.

Crop	Production to residue ratio (R)	Dry Matter Fraction (D)	Dry Matter burned in Fields % (B)	Burn Efficiency (E)
Rice	1.76[a]	0.85[a]	0.25[a]-0.80[b]	0.89[a]
Wheat	1.75[a]	0.83[a]	0.25[a]	0.86[a]
Coarse Cereals	1.5[b]	0.88[b]	0.25[c]	0.92[a f]
Total Pulses	1.5[d]	0.71[a f]	0.25[c]	0.68[a f]
Total Nine Oilseeds	0.6[a]	0.85[a]	0.25[a]	0.82[a]
Sugarcane	0.3[a]	0.71[a]	0.25[a]	0.68[a]
Cotton	3.0[e]	0.8[e]	0.25[c]	0.9[e]
Jute & Mesta	3.0[e]	0.8[e]	0.25[c]	0.9[e]

[a] (Streets et al., 2003b).
[b] (Jain et al., 2014).
[c] (IPCC, 2006).
[d] (Yang et al., 2008).
[e] (Kanabkaew and Oanh, 2011).
[f] (corn is represents for all coarse cereals whereas soybean for total pulses).

$$TEP = \Sigma_{crops}\ LHV \times \text{total amount of crop residue generated} \quad (4)$$

The energy potential of various crop residues was calculated using LHV, which is based on the ultimate analysis of the crop straw and is an important parameter to calculate the energy potential of biomass as reported in detail by Gadde et al. (2009b). The LHV in MJ/kg for different crop residues as shown in Table 2 was adopted from Koopmans and Koppejan (1997); Rahman and Paatero (2012) and Singh et al. (2008). The electricity generation in TWh was estimated using equation (5).

$$\textit{Electricity generation}\ (TWh) = \frac{\eta \times TEP}{100} \quad (5)$$

where

η = efficiency of biomass power plant (%)
TEP = theoretical energy potential (PJ)

Further, based on scientific literature various technological and non-technological mitigation measures were also examined to suggest alternative uses of crop residue and develop mitigation strategies. Criteria for the technological and non-technological mitigation measures was adopted from the United Kingdom, DEFRA and DFA (2005) and D'Elia et al. (2009).

3. Results and discussion

3.1. Total crop residue generation and proportion burnt in Indian agricultural fields

The total crop residue generated in India was calculated using IPCC (2006) guidelines on the basis of annual crop production data acquired from the Department of Agriculture (2018). The data indicate large geographical variations in total crop residue generation. In North and Northwest India major crops include wheat, rice, and sugarcane, especially in the states of Punjab and Haryana. Generally, wheat straw is used as fodder for cattle, but farmers do not prefer to use rice straw for cattle feed and hence it is burned openly in agricultural fields. Rice straw contains high silica and has low digestibility and nutritive values (Na et al., 2014) and may affect the health of livestock. Further, the sowing window between the harvesting of *kharif* crops and *rabi* crops is very short (few days), hence farmers prefer to burn the crop residue of rice in the fields.

Farmers have a longer sowing window between the *rabi* harvest and the planting of the *kharif* crop. This helps them to utilize wheat crop residue in a better manner. In south India, rice straw is not only used as fodder but also in paper factories, construction of thatch in the kutcha house (mud hut) and other applications (Gadde et al., 2009b). Venkataraman et al. (2006) reported that in India around 18–30% of crop residue is burned in the agricultural fields with large regional variations. Following the study of Jain et al. (2014) the rice straw burning in agricultural fields was considered 80% for states of Punjab, Himachal Pradesh and Haryana, 50% for Karnataka and 25% for other Indian states in the current work. Table 3 shows the amount of crop production, crop residue generated, and residue burnt in agricultural fields in India. As can be observed from Table 3 crop production has increased from 476 Mt to 618 Mt since 2003–04 to 2016–17. Similarly, the amount of crop residue burnt in agricultural fields increased from 89 Mt to 116 Mt. It is also estimated that 488 Mt of total crop residues were generated in India during 2017, and 24% of it was burnt in open agricultural fields. Trends of crop production, residue generated and burned are shown in Supplementary Fig. S1. Sahai et al. (2011) estimated 63 Mt crop residues was burned in fields, which was about 24.9% of total crop residue generated. Table 4 shows the comparative overview of crop residue burning in India. As shown in Fig. 1, rice and wheat contribute maximum to crop waste residue, i.e., 63% of the total crop primary residue. Fig. 2, shows the percentage amount of various crop residue burned in India, where rice contributed maximum (43%) followed by wheat (26%); sugarcane (10%) and coarse cereals (11%). Sahai et al. (2011) reported that wheat and rice contribute about 76% of total crop residue.

Table 2
Lower Heating Value (LHV) of different crop residues.

Crop	Lower Heating Value (MJ/kg)
Rice	16.02[a]
Wheat	12.38 [a]
Coarse Cereals	12.38 [a]
Total Pulses	12.38 [a]
Total Nine Oilseeds	12.38 [a]
Sugarcane	20 [b]
Cotton	18.61[a]
Jute & Mesta	16.91[c]

[a] (Koopmans and Koppejan, 1997).
[b] (Singh et al., 2008).
[c] (Rahman and Paatero, 2012).

3.2. Estimation of emissions of crop residue burning

The crop-specific emission factors used to estimate emissions of various air pollutants from crop residue burning were collated from various studies (Table 5). The country-specific emission factors for wheat were taken from Sahai et al. (2007) which are based on the

Table 3
Annual total crop production, residue generation and residue burnt scenario for all crops in India.

Year	Crop Production (P) (in Mt)	Crop Residue Generated (in Mt)	Residue Burnt (in Mt)
2003–04	476.79	375.84	89.60
2004–05	464.44	356.27	86.39
2005–06	522.84	383.65	92.56
2006–07	602.98	411.89	97.25
2007–08	615.13	433.02	102.59
2008–09	552.87	422.34	101.07
2009–10	541.49	400.39	96.37
2010–11	626.87	454.02	107.27
2011–12	658.15	480.37	112.86
2012–13	637.06	472.79	111.90
2013–14	658.14	487.82	115.14
2014–15	649.78	468.54	111.02
2015–16	632.26	462.39	110.05
2016–17	618.97	487.71	116.82

Table 4
Comparative overview of crop residue burning estimates for India.

Year	Crop residue burned (Mt)	References
Mid - 90s	84	Streets et al., 2003a, b
2001	116 (58–289)	Venkataraman et al., 2006
2008–09	98	Jain et al., 2014
2010	63	Sahai et al., 2011
2016–17	116	Current study

in-situ burning of wheat straw. For the crops (e.g., sugarcane), where no emission factors were available (i.e., for N_2O, PAHs), an emission factor of similar crop residue was used for air pollution emissions estimation. It was observed that there is no study, which reports the emission factors of various air pollutants for crop residue burning in India. Hence, to prepare an emissions inventory and emission factors of various air pollutants from crop residue burning were examined as summarised in Table 5. This helped to estimate the emission of fine atmospheric particles, GHGs, NMVOCs and gaseous pollutants as discussed below in detail.

3.2.1. Emission of atmospheric fine (PM_{10}, $PM_{2.5}$) particles

Table 6, shows the emissions of $PM_{2.5}$ and PM_{10} from primary crop residue burning in agricultural fields, estimated based on IPCC (2006) methodology. Table 7 shows that $PM_{2.5}$ and PM_{10} emissions were 630.70 and 624.11 Gg for the year 2003–04, which will double by the year 2050. Venkataraman et al. (2006) estimated 572–2393 Gg/yr $PM_{2.5}$ emissions from crop residue burning. However, in contrast to the above studies, Jain et al. (2014) estimated 384 Gg/yr of $PM_{2.5}$ emissions, which seems towards the lower side. Rice and wheat contribute significantly to a total emission of $PM_{2.5}$ and PM_{10} emissions from crop residue burning. The rice residue contributes 51% of the total $PM_{2.5}$ emissions followed by wheat residue, which contributes 32% of the total $PM_{2.5}$ emissions from crop residue burning. 56% of PM_{10} was emitted from rice, whereas 22% was from wheat and 7% from coarse cereal. Higher particulate matter emission from rice residue is linked to the higher amount of residue burnt and higher emission factors due to smoldering. Awasthi et al. (2011) also reported that the rice crop has higher contributions to emissions as compared to wheat residue burning. It is interesting to note that

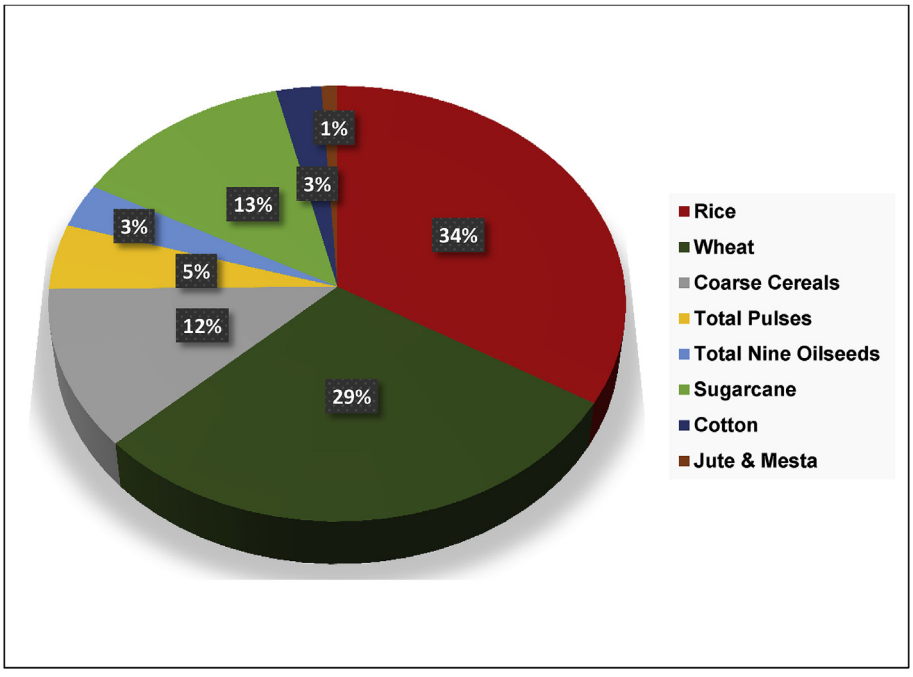

Fig. 1. Fraction of various crop residue generated in India.

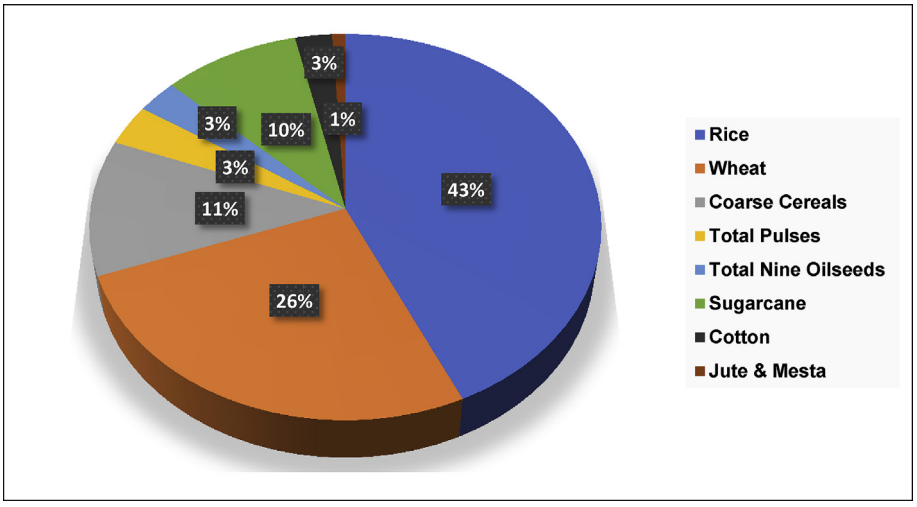

Fig. 2. Contribution of various crops residue burned in India.

Table 5
Emission factors of various crop residues burning (g kg^{-1}).

	Rice	Wheat	Coarse Cereals	Combined crops	Sugarcane	Cotton	Jute
$PM_{2.5}$	8.3	7.6 ± 4.1[a]	4.1	3.9	3.8	3.9	3.9
PM_{10}	9.1	5.7[b]	4.3	8.05	4	4.35	4.35
SO_2	0.18	0.4[b]	0.44	0.216	0.21	0.21	0.21
CO_2	1177	1787 ± 35[c]	2327	1130	1130	1345	1345
CO	93	28 ± 20[c]	114.7	86.3	34.7	105.82	105.82
NOx	2.28	1.70 ± 1.68[c]	4.3	0.7	2.6	2.49	2.49
N_2O	0.48 ± 0.45[c]	0.74 ± .46[c]	0.74 ± .46[d]	0.74 ± .46[d]	0.74 ± .46[d]	0.74 ± .46[d]	0.74 ± .46[d]
NH_3	4.1	1.3[b]	0.68	1.3	1	1.3	1.3
CH_4	9.59	3.55 ± 2.66[c]	4.4	4.56	0.4	4.56	4.56
NMVOC	7	7[d]	10	7	2.2	7	7
EC	0.51	0.16 ± 0.07[c]	0.95	0.47	0.7	0.82	0.82
OC	2.99	0.29 ± 0.12[c]	2.25	0.7	3.3	1.83	1.83
PAH	0.005[e]	0.0037 [e]	0.0017 [e]	0.0017 [d]	0.0017 [d]	0.0017 [d]	0.0017 [d]

All the emission factors are taken from (Kanabkaew and Oanh, 2011) except.
[a] (Li et al., 2007) where here we take the value as 8.3 as of our best estimates.
[b] (Yang et al., 2008).
[c] (Sahai et al., 2007).
[d] (as of authors best estimate we use the EF of other crops for unavailable EFs).
[e] (Zhang et al., 2011).

Table 6
Crop residue burning emissions of various pollutants from different crops (Gg/yr) in 2016–17.

	Rice	Wheat	Coarse Cereals	Total Pulses	Total Nine Oilseeds	Sugarcane	Cotton	Jute & Mesta	Total
$PM_{2.5}$	418.00	264.57	54.48	15.63	12.75	42.11	11.66	4.16	**823.36**
PM_{10}	458.29	175.35	57.14	32.25	26.32	44.33	13.01	4.63	**811.34**
SO_2	9.07	12.31	5.85	0.87	0.71	2.33	0.63	0.22	**31.97**
CO_2	59275.74	54974.27	30922.51	4527.50	3694.99	12523.52	4022.31	1433.11	**171373.95**
CO	4683.64	861.38	1524.20	345.77	282.19	384.57	316.46	112.75	**8510.97**
N_2O	24.17	22.76	9.83	2.96	2.42	8.20	2.21	0.79	**73.36**
NOx	114.82	52.30	57.14	2.80	2.29	28.82	7.45	2.65	**268.27**
NH_3	206.48	39.99	9.04	5.21	4.25	11.08	3.89	1.39	**281.33**
CH_4	482.97	109.21	58.47	18.27	14.91	4.43	13.64	4.86	**706.76**
NMVOC	352.53	215.34	132.89	28.05	22.89	24.38	20.93	7.46	**804.47**
EC	25.68	4.92	12.62	1.88	1.54	7.76	2.45	0.87	**57.73**
OC	150.58	8.92	29.90	2.80	2.29	36.57	5.47	1.95	**238.49**
PAH	0.26	0.04	0.02	0.01	0.01	0.02	0.01	0.00	**0.36**

$PM_{2.5}$ emissions from agriculture residue burning are slightly higher than PM_{10}. However, this due to fact that emission factors of $PM_{2.5}$ and PM_{10} are taken from different studies as there was no comprehensive study available. Similarly, Kim Oanh et al. (2011) also reported that $PM_{2.5}$ contribute to the majority of particulate matter and are about 90% of PM_{10} emissions from in situ burning of rice straw. Hence, the exposure to agriculture crop residue burning may adversely affect the human health at local and regional scale (Agarwal et al., 2013).

Table 7
The trend of crop residue burning emissions for various pollutants.

Pollutants	Crop Residue Burning Emission (Gg/yr)		
	2003–04	2016–2017	2050
$PM_{2.5}$	630.70	823.36	1193.88
PM_{10}	624.11	811.34	1176.44
SO_2	24.57	31.97	46.35
CO_2	132085.94	171373.95	248492.23
CO	6617.46	8510.97	12340.90
N_2O	56.03	73.36	106.37
NOx	209.07	268.27	388.99
NH_3	217.53	281.33	407.92
CH_4	547.61	706.76	1024.80
NMVOC	620.88	804.47	1166.48
EC	44.96	57.73	83.72
OC	186.33	238.49	345.81
PAH	0.28	0.36	0.53

3.2.2. Greenhouse gases emissions

The agriculture sector is one of the major contributors to GHG emissions, accounting for 17–32% of it as reported by Bellarby et al. (2008). Indian agriculture sector accounts for 12.2% of world's total GHG emissions from this sector, i.e., 658823 Gg CO_2 equivalent emissions (CO_2e) emissions (Maraseni and Qu, 2016). The further burning of crop residue in agricultural fields accounts for 12% of GHG emissions (Bellarby et al., 2008). Results of the current study show that GHG emissions from the crop residue burning were 171374, 706.76 and 73.35 Gg/yr for CO_2, CH_4 and N_2O for the year 2017. Venkataraman et al. (2006) estimated that emissions from agricultural residue burning ranges from 175 to 539 Tg/yr for CO_2 and 313–1164 Gg/yr for CH_4. The range of these emissions seems towards the higher side compared to the current work. Whereas, Jain et al. (2014) and Sahai et al. (2011) reported 149 Tg/yr of CO_2 and 174 ± 35 Gg/yr of CH_4 emissions respectively from crop residue burning.

Approximately 211 Tg/yr of (CO_2e) GHGs were emitted from in-situ crop residue burning in India. These GHG emissions can be avoided if crop residue can be utilized in biomass power plants to generate electricity. It is interesting to note that the CO_2 emissions from crop residue burning are not considered for net GHG emissions inventories, as the released carbon is reabsorbed during the next growing period (Sahai et al., 2011). Despite this, there are several studies, which emphasize on the CO_2 emissions reduction as GHG from crop residue burning and exchange them under Clean Development Mechanism (CDM) (Sun et al., 2016; Ravindra et al., 2016a).

3.2.3. Gaseous emissions (SO_2, CO, NOx, and NH_3)

Emissions of SO_2, CO, NOx, and NH_3 were estimated 25, 6617, 209, 218 Gg respectively for the year 2003–04, which increased to 32, 8511, 268, 281 Gg respectively for the year 2016–17. Sahai et al. (2011) reported that CO and NOx emissions were 3431 ± 709, and 140 ± 24 Gg for the year 2010. These estimates seem towards the lower side due to lower estimates of crop residue burning and difference in emission factors. Similarly, Venkataraman et al. (2006) provides a range of 46–172, 10000–74000, 289–1290, 151–560 Gg/yr for these pollutants, whereas 39.4, 9262, 6.90 and 128 Gg/yr of gaseous emissions were reported by Jain et al. (2014) respectively for SO_2, CO, NOx, and NH_3.

3.2.4. NMVOC, EC, OC and PAH emissions

As depicted in Table 7, current emissions of NMVOC, EC, and OC are 804.47, 57.73, and 238.49 Gg respectively, which will be almost doubled by 2050 from year 2003–2004. In contrast to current work Venkataraman et al. (2006) estimate NMVOC emissions towards higher side, i.e., 1818–6767 Gg/yr whereas Jain et al. (2014) reported towards lower side (39.4 Gg/yr). The burning of crop residue also results in carcinogenic pollutants such as PAHs as reported by Ravindra et al. (2001, 2008) and also highlighted that PAHs emissions factors are mainly based on wind tunnel experiments but may vary in actual field conditions.

Ravindra et al. (2008) also mentioned that PAH emissions from crop residue burning increase with an increase in $PM_{10}/PM_{2.5}$ emissions and depend mainly on wind speed, flaming rate and smoldering of crop residue. The crop residue burning emits 0.36 Gg/yr of PAHs for the year 2016–17 in India. Zhang et al. (2011) reported that 1.09 Gg/yr of PAHs emissions from crop residue burning in China. Hence, it appears that crop residue burning in China emits three times the toxic PAHs emissions than India. However, recent estimates from China are required for better comparison and to assess the effectiveness of their policy on reduction in PAHs emissions.

3.2.5. Crop residue burning estimates for 2050

The estimates of crop residue generation and their burning in the agricultural fields were calculated by using models of FAO, 2012 (Alexandratos and Bruinsma, 2012). The FAO models consider various factors such as crop yields, expansions of arable land, the intensity of agriculture, and use of fertilizers for the prediction of various crop productions. It estimates that higher yield and intensive use of land will contribute to 90% growth in crop production. Further, it is projected that in developing countries this will significantly increase the growth of wheat and rice production as the yield will increase (Alexandratos and Bruinsma, 2012). Interestingly these crops also generate maximum crop residue waste.

Having 2017, as the base year it was considered that there would be an annual growth of 1.5 percent per annum for all crops from the year 2017–2030 and after that crop production will decline to 0.9 percent per annum up to 2050 in India. The crop production will increase due to increase in cropping intensities and higher yields. Further, the decline is projected due to a reduction in arable land area (Alexandratos and Bruinsma, 2012). Thus, the annual crop production will increase from 619 Mt (2017) to 899 Mt (2050) having an increase of about 45 percent (Fig. 3). Comparison of current and future emissions of various pollutants and GHGs (CO_2e) from crop residue burning are shown in Figs. 4 and 5 for India. It shows that there will be a 45% increase in the emission of pollutants from crop residue burning if the current practices continue as per our estimations. However, there is a potential to decrease crop residue burning emissions by various technological, non-technological, and policy options as discussed in section 4.

3.3. Energy potential of the primary residue of crops

Various scenarios were generated to explore the energy potential of the crop residue generated and burnt in-situ in fields, having 2017 as the base year. The 1st scenario, considers the total generated crop residue with 100% Collection Efficiency (CE). This yields theoretical energy potential of 7236.2 PJ per annum. The 2nd scenario considers only crop residue which is burned in agricultural fields having the energy potential of 1737.5 PJ per annum. In the 3rd scenario, the total generated crop residue with the 50% collection efficiency (CE) was assumed, and it resulted in the theoretical energy potential of 3618.1 PJ per annum. The projection of energy potential and electricity generation are shown in Table 8.

As highlighted by McKendry (2002) the conversion efficiency of combustion-based biomass power plants ranges from 20 to 40%. However, higher efficiencies can be achieved in a large capacity power plant. Considering the direct combustion method for the electricity generation with the maximum efficiency (η) of 25%, the

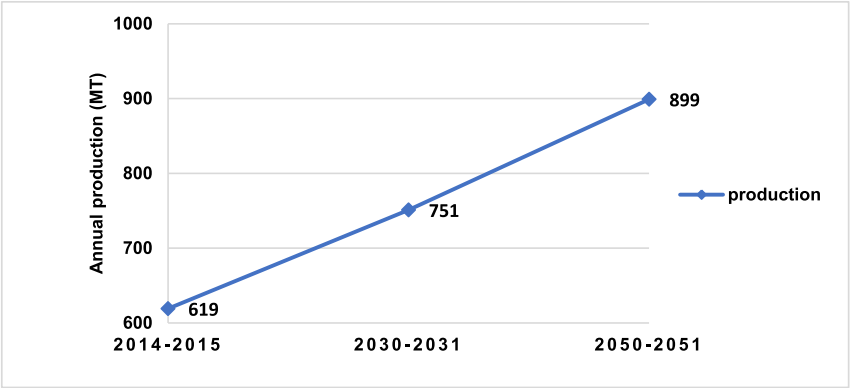

Fig. 3. Estimated growth in current crop production up to 2050–51 for India.

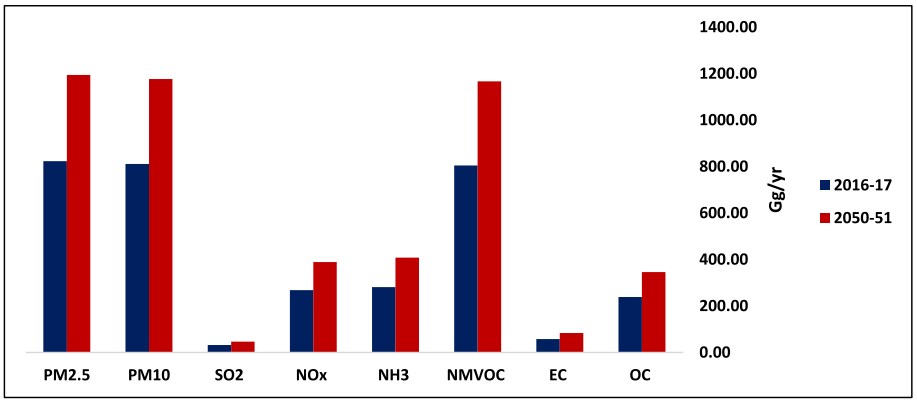

Fig. 4. Comparison of current and future emissions of various pollutants from crop residue burning for India.

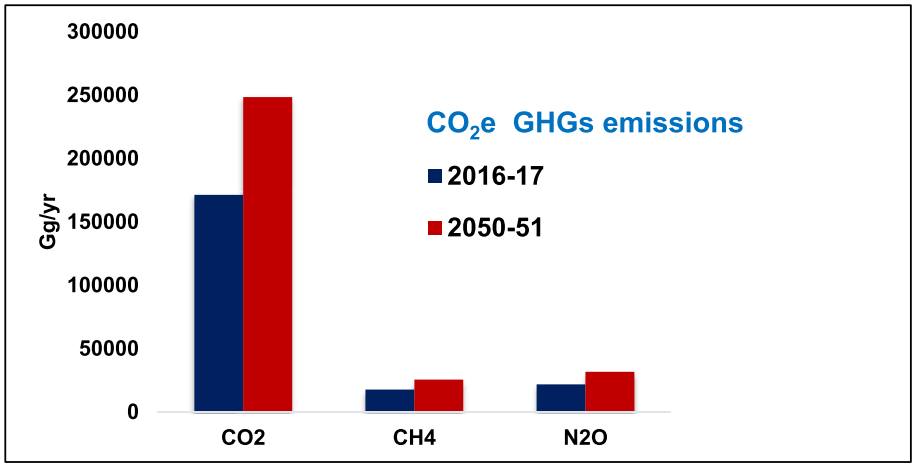

Fig. 5. Current and future emission of various GHGs (CO_2e) from crop residue burning in India.

Table 8
Energy potential and electricity generation estimates of crop residue.

Crop residue	Theoretical energy potential (PJ)	Electricity generation (TWh)	
		$\eta = 25\%$	$\eta = 50\%$
1st - Total generated (CE = 100%)	7236.27	502.5	1005
2nd - Burnt insitu only (CE = 100%)	1737.57	120.6	241.3
3rd - Total generated having CE = 50%	3618.13	251.2	502.5

electricity generation for the above scenarios will be 502.5 TWh, 120.6 TWh, and 251.2 TWh respectively. If the direct combustion method has 50% efficiency (η), the electricity generation for different scenarios will be 1005 TWh, 241.3 TWh, and 502.5 TWh, respectively. The current work shows that if all the crop residue (which is currently burned in agricultural fields) will be used for energy production, it can produce 120 TWh of electricity. This accounts for 10% of the current energy production in India. Singh (2017) also highlighted that the implementation of appropriate technology and policies could help to exploit the potential of crop residue-based electricity to a great extent.

4. Mitigation of crop residue burning emissions and strategies for cleaner emissions

The primary residue of crops is usually burned in fields or can be used as livestock feed, compost, cattle house flooring, and conditioning material for agricultural fields. Further, some proportion of it also plows into fields used for handicraft, cooking fuel, and papermaking (Romasanta et al., 2017). There are several studies which highlighted that the integration of economic factors, environmental factors, and energy policies could improve the utilization of crop residue (Pandey and Soccol, 2000; Shafie, 2016). Considering this, scientific literature was examined to assess the various technological, non-technological, and policy options for the sustainable use of crop residues as discussed below. Appraisal of various options helped in developing an integrated sustainable crop residue management model as depicted in Fig. 6. This model suggests various alternative options which can be applied synergistically depending on the type of agricultural residue, geographic location, seasons and availability of resources to manage crop residue in an environmentally sound manner. Further, merits and implementation challenges to adopt alternative practices are also discussed in the subsequent sections.

4.1. Technological mitigation options and challenges

There are various technology-based mitigation options which have the potential to transform crop residue into other usable products. These alternative options will not only help to reduce air pollution and GHG emissions from crop residue burning but also limit the adverse impacts of climate change.

4.1.1. Biomass energy generation

Energy crisis is one of the major challenges to attain sustainable development especially in developing countries where energy demand is growing rapidly (Mekhilef et al., 2011). Crop residues having lignocellulosic biomass are considered most effective for the production energy through gasification, biomethanation, and ethanol generation (Shafie, 2016). In India, around 500 biomass power and cogeneration plants have been installed by the Ministry of New and Renewable Energy (MNRE, 2016). These biomass power plants generate 11.5% of the total renewable power supply (Energy statistics, 2017). However, a fraction of renewable energy could be enhanced by application of advanced technology with higher energy efficiency and ensuring availability of biomass or crop residue throughout the year.

The energy production from the crop residues is an emerging area and offers various technological options as mentioned in Fig. 6. Further, as discussed above, there are many challenges in properly

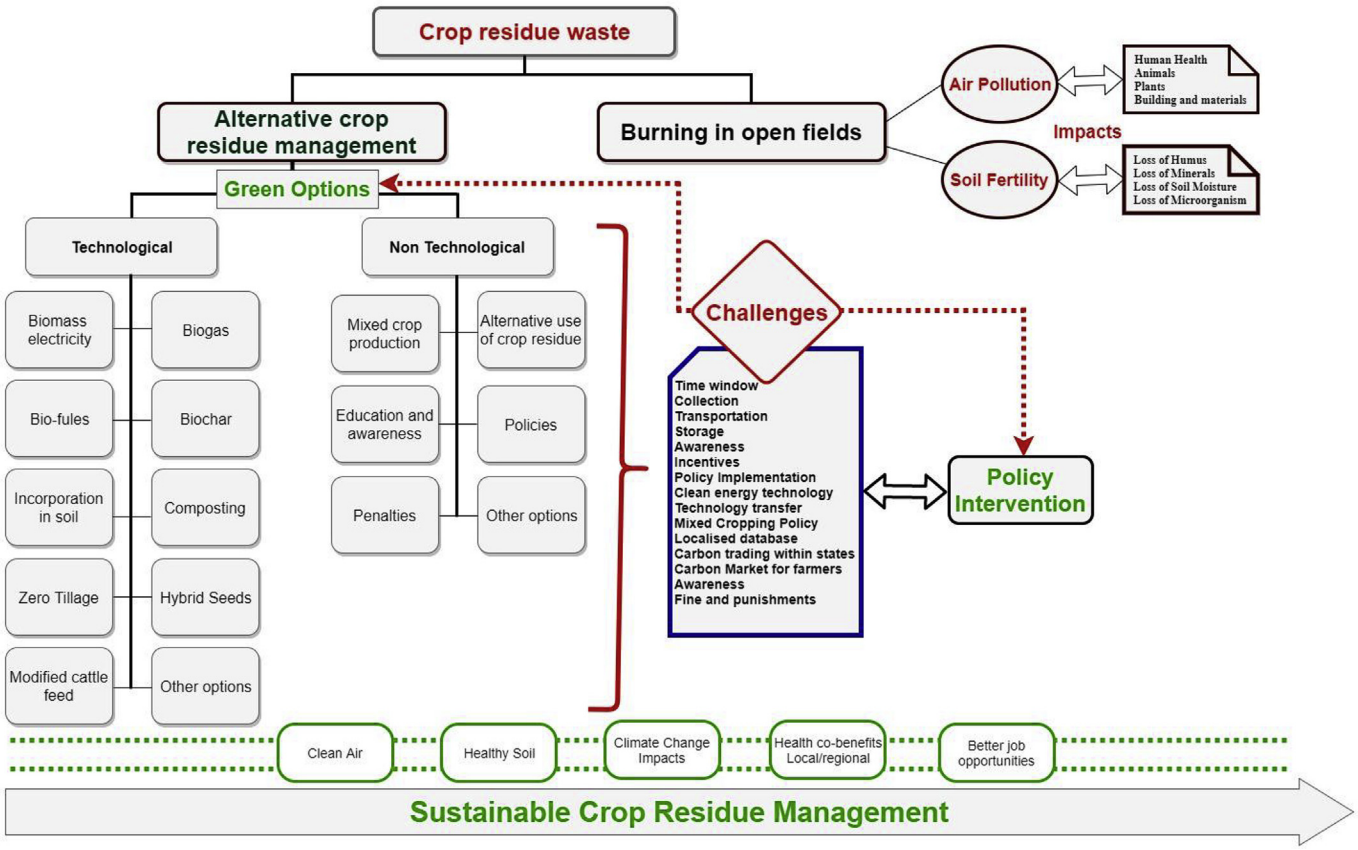

Fig. 6. Model of sustainable crop residue management options and benefits.

utilizing crop residue from a pilot scale to a practical scale. There is also a need for financial incentives to promote the growth in biomass power sector.

Biomass power accounts for only 1.46% of total estimated potential renewable power in 2016 in India (Energy Statistics, 2017). Hiloidhari et al. (2014) reported that the annual bioenergy potential from the surplus residue is around 17% of energy consumption of India. Current work also shows that biomass power plants in India can produce 120 TWh of electricity, which is 10% of the current energy production. Even the small biomass-based power generation systems have the same potential to generate grid standard electricity as highlighted by Dasappa et al. (2011). Up to 75% efficiency has been achieved by circulating fluidized-bed (CFB) gasifier and down draft gasifier in China (Zeng et al., 2007). Further, the generation of biogas from various crop residues at the village level can help as low-cost cooking fuel along with the benefit of manure management of crop residue at the local level. The government should support initiatives to build biogas plants and provide training to the users. The use of biogas in the rural household for cooking will help to reduce the household air pollution and associated health risks (Ravindra et al., 2016a).

Further, conversion of biogas to biomethane offers the potential for commercial uses. Biomethanation plant users also co-benefited by organic fertilizer from biogas residue (Hiloidhari et al., 2014; Sun et al., 2016). Crop residue can also be used to produce biofuels and other useful products like bio-oil. The engagement of local youth in its production and distribution will offer employment and will generate a local market to further enhance the production. The active participation of the community in biomass energy production could be ensured through some rewarding mechanism.

4.1.2. Biochar and composting

A report by the Joint Research Centre, European Union (Verheijen et al., 2010) highlighted that conditioning of soil by adding biochar helps to hold the soil carbon for hundreds of years. Amendment of soil by biochar improves plant health and their growth. Crop residue, by the process of pyrolysis, can be utilized to produce biochar. Mohammadi et al. (2016) also highlighted that production of biochar locally from crop residues can help to reduce 38–49% carbon footprints from rice production. Hence, uses of biochar in agricultural practices is a sustainable alternative, which could also help to mitigate climate change as it helps in carbon sequestration.

The production of compost from various crop residues and its use in agricultural fields is an environmentally friendly technique. Further, it can also help in generating local employment and economic benefits (Mor et al., 2016). Gupta and Garg (2011) highlighted that agricultural waste is a nutrient-rich feed for earthworms and the use of earthworms yields good quality compost. Similarly, Singh and Sharma (2002) also reported that integration of bioinoculants together with vermicomposting result in good quality compost from wheat straw. Bansal and Kapoor (2000) have shown the application of mustard and sugarcane residue for generating vermicompost by mixing it with cow dung. Suthar (2008) conducted a similar kind of study for wheat, millets, and pulse residue along with cattle shed waste by using the epigeic earthworms, and they concluded that it results in a value-added product of vermicompost. Similar kinds of experiments were also performed by Sharma and Garg (2018). However, there is a need to train farmers to adopt such eco-friendly approaches which will also improve the crop yield.

4.1.3. Incorporation of straw in the soil, application of happy seeder and zero tillage

The incorporation of crop straw into the soil helps to retain the soil organic matter, water and hence plays a vital role in maintaining soil structure and nutrient cycles (Powlson et al., 2008). The methods of straw incorporation in the soil improve soil fertility as crop residue straw naturally contain nutrients such as nitrogen, phosphorus, potassium (Yin et al., 2017). Pathak et al. (2006) also reported that incorporation of rice straw in soil with some amount of inorganic nitrogen or microbial inoculation results in same crop yield of wheat crop as without incorporation and with the use of fertilizers. Crop incorporation reduces the requirement of artificial nutrients as fertilizers. However, the process of incorporation remains a major challenge to make it a regular practice as it requires suitable machinery and is considered labor-intensive (Dobermann and Fairhurst, 2002).

The zero tillage, also known as direct drilling, is usually recommended for the sowing of crops (Roy et al., 2018). Zero tillage practice helps in maintaining an organic matter of topsoil and the nutrient-rich humus acts as compost for the crop (Sidhu et al., 2007, 2015). De Vita et al. (2007) reported that weather conditions, soil water evaporation, and soil water availability play a vital role in achieving the same grain yield as by any other cultivation method. However, Song et al. (2016) reported that incorporation of straw and tillage practices could increase rice yield up to 9% compared to the traditional practices. Further, zero tillage approach significantly reduces the production cost of grains. Hence, it is evident that these practices not only enhance soil carbon preservation capacity but also increase crop yield.

Indigenous machines like happy seeders are recommended for straw management (Roy et al., 2018), which minimally disturb the topsoil to sow the crop. Happy seeder performs the straw mulching and seed drilling using the same machine system. Therefore, application of happy seeder helps in replenishing the soil quality and in reducing the use of fertilizers including carbon sequestering. Sidhu et al. (2015) reported that wheat grown by happy seeder has similar or even higher grain yields as compared to conventional tillage. Hence, there is a scope to promote indigenous machines which are readily available in the local market.

4.1.4. Promotion of hybrid seeds and use of crop residue as nutrient livestock feed

Farmers have very short sowing window between the harvest and sowing of the next crop especially after kharif crops in north India. Short sowing window forces farmers towards crop residue burning to clear agricultural fields for the next crop. The use of hybrid crop seeds, which have a shorter growing period and produce less crop residue can help to increase the sowing timeframe. The suitable time duration between crop sowing will provide farmers time for better crop residue management.

The use of crop residue for livestock as fodder is a regular practice in many rural parts of India. The straw of some crop residues like wheat and maize are generally used as fodder for cattle. However, rice straw contains high silica resulting in low digestibility and nutritive values for livestock (Na et al., 2014), therefore, confines the uses of rice straw as livestock feed. Hence, there is a need to develop technologies which can modify raw crop residue into processed feed. Further, enchaining crop residue nutrients through fortification can also help in commercializing the crop residue and its uses as nutrient-rich livestock feed.

4.1.5. Nano silica production and other uses

Agro-industry waste can also be utilized to produce an industrial product such as nano silica (Mor et al., 2017). Amorphous nano silica produced using crop residue has been found to be cost-effective (Mor et al., 2017) and can be utilized as a raw material for manufacturing nanomedicines, cosmetics, solar cells, etc. This shows that there is a potential to convert crop residue into valuable

commercial products which in turn can also increase the farmers' income.

The crop residues are mostly formed of cellulose, hemicellulose, and lignin (Zhang et al., 2017). They can be used to prepare biodegradable and compostable materials such as dinnerware (disposable leaf and straw plates/bowls), cardboard and packaging materials instead of plastic. These products require short training and minimum machinery to start micro and small enterprises.

4.1.6. Challenges for technological mitigation of crop residue burning

The collection, transportation, and storage of crop residue to prepare feedstock for further use is one of the major challenges in supply chain. The straw is widely spread and farmers do not have the time to pre-process straw during harvest and next sowing season (Liu et al., 2017). Crop residues are bulky and hence require a large storage space. Most of the farmers in India hold small lands (Agriculture Census, 2011) and need to clear it for the sowing of the next crop.

The logistics cost of crop residue from the farm to processing unit increases the cost of the end product. The briquetting of crop residue is a good alternative for their storage and transportation. However, briquetting is a mechanical process and its economic viability for Indian farmers still needs to be examined. Exploration of high potential of biomass energy requires advanced technology and high investment cost. This can be achieved by giving incentive under CDM projects as reported by Purohit and Michaelowa (2007).

Incentives at the village level should be given to build biogas and composting plants for individual and commercial uses. Engagement of locals to manage these plants can help to generate employment and to increase their income. The mechanization of agricultural sector will also help in better management of crop residue. Nguyen et al. (2016) mentioned that mechanized rice straw collection could reduce in-field burning and generate feedstock, which can be processed in various sustainable ways. The availability of crop residue throughout the year for commercial activities like power generation is a challengeable task as the crop residue is generally available for a time period too short to depend on the cropping type and pattern. To overcome this problem, a localized biomass database needs to be established as a key aspect of decentralized bioenergy programs (Hiloidhari et al., 2014). Urban forestry can fulfill the shortage of biomass for power plants and forest leaves waste for their uninterrupted running (Mor et al., 2016; Ravindra et al., 2015).

Most of the farmers in India cultivate on small lands (Agriculture Census, 2011) and cannot afford the heavy machinery to mobilize their crop residues from the farm to the processing units. The organized or formal market for the biomass business should be made available where farmers can directly sell their crop residue. Hybrid crop seed with high yield, which can be grown in the shorter time frame needed to be made available in the market and farmers should be educated to use them. There are several studies which report the uses of biomass for energy generation from crop residues (Hiloidhari et al., 2014; Kim and Dale, 2004; Zeng et al., 2007). However, most of these studies are at the laboratory scale and need to be commercialized for large-scale energy production from biomass.

4.2. Non-technological mitigation options and challenges

4.2.1. Mixed crop production

Mixed cropping policy can help to break the chain of traditional cropping system. The traditional crops like rice and wheat can be replaced by alternative crops with higher nutrient value and should be used as fodder and manure. Arunrat et al. (2016) also mentioned that alternative crop rotation system with selective crops could effectively reduce the GHG emissions from paddy fields. Further, alternative cropping system will help to increase the monitory benefits of farmers. Li et al. (2017) highlighted that adopting agriculture recycling systems will help to reduce GHG emission significantly and will help to increase the crop yield.

4.2.2. Enhancing education and awareness and promotion of the alternative use of crop residue

There is a need to increase awareness and education of the farmer community to promote alternative uses of crop residues through various public meetings, workshops, and training programs at the local and regional level. Further, farmers should also be made aware of the adverse effects of crop residue burning on human health and the environment on a regular basis (Agarwal et al., 2014; Ravindra et al., 2016a). Farmers should be educated through pilot demonstrations of alternative uses of crop residue burning. Local youth, students, and other voluntary organizations should be engaged to create awareness as has been done in other cases (Ravindra et al., 2016b). Tier-level fines and punishments for the violators should be displayed at prominent locations in villages. The crop residues are also used in various other areas such as in mushroom production, bedding material for livestock, roof thatching, packing material, mulching material, construction material, handicrafts, etc. These should be promoted and subsidized through various eco-friendly schemes.

4.2.3. Challenges for non-technological mitigation of crop residue burning

Awareness among farmers with respect to the alternate uses of crop residue needs to be enhanced by conducting regular programmes under Panchayati Raj (local self −government) schemes. Further, the focus should be on sharing real success stories to influence farmers for alternative uses of crop residue. Mechanism and budget to provide subsidy and financial support for farmers should be made easy. Farmers, who will use the alternative crop pattern should be provided with a hassle-free financial support from the government.

It is difficult to identify the violators of crop residue burning and to punish them effectively. This can be achieved by strengthening air quality monitoring and surveillance network. Use of remote sensing to monitor air pollutants and hotspot identification from agricultural burning should be made a routine practice (Ravindra et al., 2016a). This will also help to measure the local, regional, and global impact of crop residue burning on air quality and human health.

4.3. Building policies for better crop residue management

Implementation of both technical and non-technical mitigation options needs to be promoted through suitable policies and planning such as easy credit schemes to buy advance machinery or to initiate small enterprises. Innovative research and investments need to be prompted in agro-industry. This can help in the modernization of agricultural practices. Technologies that minimize the use of water, fertilizers, and pesticides should be subsidized for better management of crop residue. Further, the local market should be developed for agricultural products and by-products. There is a need to promote agricultural entrepreneurship to modernize the agricultural sector and incentives for their start-ups should be encouraged.

Electricity generation from biomass energy-based small rural enterprises can be brought under rural development plans. Balachandra (2011) highlighted that farmers and the local population should be supported to initiate small rural biomass energy

enterprises. The subsidy or tax exemption for biomass power plants should be promoted to utilize crop residue as fuel. Industries buying electricity from biomass power plants should be given rebate and tax credits. Clean energy technology and technology transfer should be prompted under CDM. Sun et al. (2016) also suggested that GHG emissions from agricultural crop residue burning should be reduced by policy regulation and by commercializing the energy production using biomass.

The mechanism of carbon trading within the states of a country and carbon market for farmers should be created and promoted. This will help farmers to gain financially by adopting not burning the crop residues. Inter-state setup for crop residue should be made easy, and they should be allowed exchange carbon credits. There is a lack of a system to promote farmers innovations and to promote them through suitable reward mechanism. Agricultural universities should be engaged to develop model villages, and more funding should be provided by the government to promote research and identify sustainable alternatives. The capacity of local and regional research institutes and universities should build for the use of new technologies, e.g., remote sensing. This will help to track the burning of crop residue on a real-time basis, and the information can be verified at fields for effective control of crop residue burning. The inter and intradepartmental cooperation between the various central and state agencies and linking with the improvement of agricultural sector needed to be improved. Further, their role and responsibilities should be defined clearly for better coordination and promotion of sustainable agricultural practices.

4. Conclusions

Crop residue burning in agricultural fields lead to the emission of various pollutants. These pollutants possess a serious threat to human health, earth climate, and the environment. This study estimated that 24% of the of crop residue (116 Mt) was burnt in 2017, leading to the annual emission of PM_{10} (812 Gg), $PM_{2.5}$ (824 Gg), EC (58 Gg) and OC (239 Gg) and GHGs (211 Tg). If the current practices of crop residue burning continue, atmospheric emissions will increase by 45% in 2050 compared to the base level of 2017. However, crop residue can be utilized for energy production in biomass power plants and has the potential to meet 10% of current energy demand of India. However, increasing the collection and transportation of crop residue from the farm to the power plants is a major challenge. The reduction in GHG emissions can also be traded under CDM, which leads to the co-benefiting in energy generation and pollution mitigation. Further, several alternative approaches were also evaluated, resulting in an integrated sustainable crop residue management model. This model can be applied synergistically depending on the type of agricultural residue and season to minimize the adverse impact of crop residue burning. Further, the estimate of crop residue burning will be useful in curbing air pollution and better planning of mitigation strategies.

Acknowledgments

Ravindra Khaiwal would like to thank Department of Health Research, Indian Council of Medical Research, Ministry of Health and Family Welfare via Letter number V–25011/25(19)2013/HR dated 16 October 2014, for providing the Fellowship Training Programme in Environmental Health under Human Resource Development Health Research Scheme. Tanbir Singh is thankful to the UGC, New Delhi for providing the financial assistance to carry out the Ph.D. research work.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2018.10.031.

References

Agarwal, R., Awasthi, A., Mittal, S., Singh, N., Gupta, P.K., 2010. Effects of air pollution on respiratory parameters during the wheat-residue burning in Patiala. J. Med. Eng. Technol. 34 (1), 23–28.

Agarwal, R., Awasthi, A., Singh, N., Mittal, S.K., Gupta, P.K., 2013. Epidemiological study on healthy subjects affected by agriculture crop-residue burning episodes and its relation with their pulmonary function tests. Int. J. Environ. Health Res. 23 (4), 281–295.

Agarwal, R., Awasthi, A., Mittal, S.K., Singh, N., Gupta, P.K., 2014. Statistical model to study the effect of agriculture crop residue burning on healthy subjects. Mapan 29 (1), 57–65.

Agriculture Census, 2011. All India Report on Agriculture Census 2010-11. http://agcensus.nic.in/document/ac1011/reports/air2010-11complete.pdf.

Akagi, S.K., Yokelson, R.J., Wiedinmyer, C., Alvarado, M.J., Reid, J.S., Karl, T., Crounse, J.D., Wennberg, P.O., 2011. Emission factors for open and domestic biomass burning for use in atmospheric models. Atmos. Chem. Phys. 11, 4039–4072. https://doi.org/10.5194/acp-11-4039-2011.

Alexandratos, N., Bruinsma, J., 2012. No. 3. World Agriculture towards 2030/2050: the 2012 Revision, vol. 12. FAO, Rome. ESA Working paper.

Arunrat, N., Wang, C., Pumijumnong, N., 2016. Alternative cropping systems for greenhouse gases mitigation in rice field: a case study in Phichit province of Thailand. J. Clean. Prod. 133, 657–671. https://doi.org/10.1016/j.jclepro.2016.05.137.

Awasthi, A., Singh, N., Mittal, S., Gupta, P.K., Agarwal, R., 2010. Effects of agriculture crop residue burning on children and young on PFTs in North West India. Sci. Total Environ. 408 (20), 4440–4445.

Awasthi, A., Agarwal, R., Mittal, S.K., Singh, N., Singh, K., Gupta, P.K., 2011. Study of size and mass distribution of particulate matter due to crop residue burning with seasonal variation in rural area of Punjab, India. J. Environ. Monit. 13 (4), 1073–1081.

Awasthi, A., Hothi, N., Kaur, P., Singh, N., Chakraborty, M., Bansal, S., 2017. Elucidative analysis and sequencing of two respiratory health monitoring methods to study the impact of varying atmospheric composition on human health. Atmos. Environ. 171, 32–37.

Balachandra, P., 2011. Modern energy access to all in rural India: an integrated implementation strategy. Energy Pol. 39, 7803–7814. https://doi.org/10.1016/j.enpol.2011.09.026.

Bansal, S., Kapoor, K., 2000. Vermicomposting of crop residues and cattle dung with Eisenia foetida. Bioresour. Technol. 73, 95–98. https://doi.org/10.1016/S0960-8524(99)00173-X.

Bellarby, J., Foereid, B., Hastings, A.F.S.J., Smith, P., 2008. Cool Farming: climate impacts of agriculture and mitigation potential. Greenpeace Int 44. http://eprints.lancs.ac.uk/68831/1/1111.pdf.

Bencs, L., Ravindra, K., de Hoog, J., Rasoazanany, E.O., Deutsch, F., Bleux, N., Berghmans, P., Roekens, E., Krata, A., Van Grieken, R., 2008. Mass and ionic composition of atmospheric fine particles over Belgium and their relation with gaseous air pollutants. J. Environ. Monitor. 10 (10), 1148–1157.

Bencs, L., Ravindra, K., de Hoog, J., Spolnik, Z., Bleux, N., Berghmans, P., Deutsch, F., Roekens, E., Van Grieken, R., 2010. Appraisal of measurement methods, chemical composition and sources of fine atmospheric particles over six different areas of Northern Belgium. Environ. Poll. 158 (11), 3421–3430.

Chandra, B.P., Sinha, V., 2016. Contribution of post-harvest agricultural paddy residue fires in the NW Indo-Gangetic Plain to ambient carcinogenic benzenoids, toxic isocyanic acid and carbon monoxide. Environ. Int. 88, 187–197.

Chen, J., Li, C., Ristovski, Z., Milic, A., Gu, Y., Islam, M.S., Wang, S., Hao, J., Zhang, H., He, C., Guo, H., 2017. A review of biomass burning: emissions and impacts on air quality, health and climate in China. Sci. Total Environ. 579, 1000–1034.

Crutzen, P.J., Andreae, M.O., 1990. Biomass burning in the tropics: impact on atmospheric chemistry and biogeochemical cycles. Science (80) 250, 1669–1678. https://doi.org/10.2307/2878539.

D'Elia, I., Bencardino, M., Ciancarella, L., Contaldi, M., Vialetto, G., 2009. Technical and Non-Technical Measures for air pollution emission reduction: the integrated assessment of the regional Air Quality Management Plans through the Italian national model. Atmos. Environ. 43 (39), 6182–6189.

Dasappa, S., Subbukrishna, D.N., Suresh, K.C., Paul, P.J., Prabhu, G.S., 2011. Operational experience on a grid connected 100 kWe biomass gasification power plant in Karnataka, India. Energy Sustain. Dev. 15 (3), 231–239.

De Vita, P., Di Paolo, E., Fecondo, G., Di Fonzo, N., Pisante, M., 2007. No-tillage and conventional tillage effects on durum wheat yield, grain quality and soil moisture content in southern Italy. Soil Tillage Res. 92, 69–78. https://doi.org/10.1016/j.still.2006.01.012.

Defra, DfT, 2005. Technical and Non-technical Options to Reduce Emissions of Air Pollutants from road Transport. https://ukair.defra.gov.uk/assets/documents/reports/cat09/0504061608_ED48300_04-04-05.pdf.

DOA, 2018. Department of Agriculture, Cooperation and Farmers Welfare, India. http://agricoop.nic.in/.

Dobermann, A., Fairhurst, T.H., 2002. Rice straw management. Better Crops Int. 16

(1), 7–11.
Energy statistics, 2017. http://www.mospi.nic.in/sites/default/files/publication_reports/Energy_Statistics_2017r.pdf.pdf.
Gadde, B., Bonnet, S., Menke, C., Garivait, S., 2009a. Air pollutant emissions from rice straw open field burning in India, Thailand and the Philippines. Environ. Pollut. 157, 1554–1558. https://doi.org/10.1016/j.envpol.2009.01.004.
Gadde, B., Menke, C., Wassmann, R., 2009b. Rice straw as a renewable energy source in India, Thailand, and the Philippines: overall potential and limitations for energy contribution and greenhouse gas mitigation. Biomass Bioenergy 33, 1532–1546. https://doi.org/10.1016/j.biombioe.2009.07.018.
Gupta, R., Garg, V.K., 2011. Potential and possibilities of vermicomposting in sustainable solid waste management: a review. Int. J. Environ. Waste Manag. 7 (3–4), 210–234.
Gurjar, B.R., Ravindra, K., Nagpure, A.S., 2016. Air pollution trends over Indian megacities and their local-to-global implications. Atmos. Environ. 142, 475–495. https://doi.org/10.1016/j.atmosenv.2016.06.030.
Hiloidhari, M., Das, D., Baruah, D.C., 2014. Bioenergy potential from crop residue biomass in India. Renew. Sustain. Energy Rev. 32, 504–512. https://doi.org/10.1016/j.rser.2014.01.025.
IPCC, 2006. IPCC Guidelines for National Greenhouse Gas Inventories. In: Eggleston, H.S., Buendia, L., Miwa, K., Ngara, T., Tanabe, K. (Eds.), Prepared by the National Greenhouse Gas Inventories Programme. IGES, Japan, p. 2006.
Jain, N., Bhatia, A., Pathak, H., 2014. Emission of air pollutants from crop residue burning in India. Aerosol Air Qual. Res. 14, 422–430. https://doi.org/10.4209/aaqr.2013.01.0031.
Kanabkaew, T., Oanh, N.T.K., 2011. Development of spatial and temporal emission inventory for crop residue field burning. Environ. Model. Assess. 16, 453–464. https://doi.org/10.1007/s10666-010-9244-0.
Kaskaoutis, D.G., Kumar, S., Sharma, D., Singh, R.P., Kharol, S.K., Sharma, M., Singh, A.K., Singh, S., Singh, A., Singh, D., 2014. Effects of crop residue burning on aerosol properties, plume characteristics, and long-range transport over northern India. J. Geophys. Res. Atmos. 119, 5424–5444. https://doi.org/10.1002/2013JD021357.
Kim, S., Dale, B.E., 2004. Global potential bioethanol production from wasted crops and crop residues. Biomass Bioenergy 26 (4), 361–375.
Kim Oanh, N.T., Ly, B.T., Tipayarom, D., Manandhar, B.R., Prapat, P., Simpson, C.D., Sally Liu, L.J., 2011. Characterization of particulate matter emission from open burning of rice straw. Atmos. Environ. 45, 493–502. https://doi.org/10.1016/j.atmosenv.2010.09.023.
Koopmans, A., Koppejan, J., 1997. Agricultural and forest residues - generation, utilization and availability. Reg. Consult. Mod. Appl. Biomass Energy 6–10. https://doi.org/10.1016/S0251-1088(83)90310-8.
Li, X., Wang, S., Duan, L., Hao, J., Li, C., Chen, Y., Yang, L., 2007. Particulate and trace gas emissions from open burning of wheat straw and corn stover in China. Environ. Sci. Technol. 41, 6052–6058. https://doi.org/10.1021/es0705137.
Li, Z., Sui, P., Yang, X., Dai, H., Wang, X., Long, P., Yan, L., Chen, Y., 2017. Balancing GHG mitigation and food security through agricultural recycling systems: case studies in the North China Plain. J. Clean. Prod. 157, 222–231. https://doi.org/10.1016/j.jclepro.2017.04.136.
Liu, B., Wu, Q., Wang, F., 2017. Regional optimization of new straw power plants with greenhouse gas emissions reduction goals: a comparison of different logistics modes. J. Clean. Prod. 161, 871–880. https://doi.org/10.1016/j.jclepro.2017.06.015.
Maraseni, T.N., Qu, J., 2016. An international comparison of agricultural nitrous oxide emissions. J. Clean. Prod. 135, 1256–1266. https://doi.org/10.1016/j.jclepro.2016.07.035.
McCarty, J.L., Korontzi, S., Justice, C.O., Loboda, T., 2009. The spatial and temporal distribution of crop residue burning in the contiguous United States. Sci. Total Environ. 407 (21), 5701–5712.
McKendry, P., 2002. Energy production from biomass (part 2): conversion technologies. Bioresour. Technol. 83 (1), 47–54.
McNeill, V.F., 2017. Atmospheric aerosols: clouds, chemistry, and climate. Annual Rev. Chem. Biomol. Eng. 8, 427–444.
Mekhilef, S., Saidur, R., Safari, A., Mustaffa, W.E.S.B., 2011. Biomass energy in Malaysia: current state and prospects. Renew. Sustain. Energy Rev. 15, 3360–3370. https://doi.org/10.1016/j.rser.2011.04.016.
Ministry of New and Renewable Energy, (2016) http://mnre.gov.in/schemes/grid-connected/biomass-powercogen/.
Mohammadi, A., Cowie, A., Anh Mai, T.L., De La Rosa, R.A., Kristiansen, P., Brandão, M., Joseph, S., 2016. Biochar use for climate-change mitigation in rice cropping systems. J. Clean. Prod. 116, 61–70. https://doi.org/10.1016/j.jclepro.2015.12.083.
Mor, S., Kaur, K., Khaiwal, R., 2016. SWOT analysis of waste management practices in Chandigarh, India and prospects for sustainable cities. J. Environ. Biol. 37 (3), 327.
Mor, S., Manchanda, C.K., Kansal, S.K., Ravindra, K., 2017. Nanosilica extraction from processed agricultural residue using green technology. J. Clean. Prod. 143, 1284–1290.
Na, Y.J., Lee, I.H., Park, S.S., Lee, S.R., 2014. Effects of combination of rice straw with alfalfa pellet on milk productivity and chewing activity in lactating dairy cows. Asian-Australas. J. Anim. Sci. 27, 960–964. https://doi.org/10.5713/ajas.2013.13597.
Nguyen, H. Van, Nguyen, C.D., Tran, T. Van, Hau, H.D., Nguyen, N.T., Gummert, M., 2016. Energy efficiency, greenhouse gas emissions, and cost of rice straw collection in the mekong river delta of vietnam. Field Crop. Res. 198, 16–22. https://doi.org/10.1016/j.fcr.2016.08.024.
Oanh, N.T.K., Permadi, D.A., Hopke, P., Smith, K., Dong, N.P., Dang, A.N., 2018. Annual Emissions of Air Toxics Emitted from Crop Residue Open Burning in Southeast Asia over the Period of 2010–2015. Atmospheric Environment.
Pandey, A., Soccol, C.R., 2000. Economic utilization of crop residues for value addition: a futuristic approach. J. Sci. Ind. Res. (India). 59, 12–22.
Pathak, H., Singh, R., Bhatia, A., Jain, N., 2006. Recycling of rice straw to improve wheat yield and soil fertility and reduce atmospheric pollution. Paddy Water Environ. 4, 111–117. https://doi.org/10.1007/s10333-006-0038-6.
Powlson, D.S., Riche, A.B., Coleman, K., Glendining, M.J., Whitmore, A.P., 2008. Carbon sequestration in European soils through straw incorporation: limitations and alternatives. Waste Manag. 28, 741–746. https://doi.org/10.1016/j.wasman.2007.09.024.
Purohit, P., Michaelowa, A., 2007. CDM potential of bagasse cogeneration in India. Energy Pol. 35, 4779–4798. https://doi.org/10.1016/j.enpol.2007.03.029.
Rahman, M.M., Paatero, J.V., 2012. Electricity generation from agricultural residues in five south Asian countries: prospects and potential. In: 4th Int. Conf. Sustain. Energy Environ. (SEE 2011), pp. 27–35. https://doi.org/10.1017/CBO9781107415324.004.
Ramanathan, V., Chung, C., Kim, D., Bettge, T., Buja, L., Kiehl, J.T., Washington, W.M., Fu, Q., Sikka, D.R., Wild, M., 2005. Atmospheric brown clouds: impacts on South Asian climate and hydrological cycle. Proc. Natl. Acad. Sci. Unit. States Am. 102 (15), 5326–5333.
Ravindra, K., Mittal, A.K., Van Grieken, R., 2001. Health risk assessment of urban suspended particulate matter with special reference to polycyclic aromatic hydrocarbons: a review. Rev. Environ. Health.
Ravindra, K., Sokhi, R., Van Grieken, R., 2008. Atmospheric polycyclic aromatic hydrocarbons: source attribution, emission factors and regulation. Atmos. Environ. https://doi.org/10.1016/j.atmosenv.2007.12.010.
Ravindra, K., Kaur, K., Mor, S., 2015. System analysis of municipal solid waste management in Chandigarh and minimization practices for cleaner emissions. J. Clean. Prod. 89, 251–256.
Ravindra, K., Sidhu, M.K., Mor, S., John, S., Pyne, S., 2016a. Air pollution in India: bridging the gap between science and policy. J. Hazardous, Toxic, Radioact. Waste 20, A4015003. https://doi.org/10.1061/(ASCE)HZ.2153-5515.0000303.
Ravindra, K., Tripathy, J.P., Tripathy, N.K., 2016b. Dynamics of Multi-stakeholder Engagement and its Role in Achieving High Compliance of a Tobacco Control Programme, vol. 3. World Development Perspectives, pp. 7–11.
Romasanta, R.R., Sander, B.O., Gaihre, Y.K., Alberto, M.C., Gummert, M., Quilty, J., Nguyen, V.H., Castalone, A.G., Balingbing, C., Sandro, J., Correa, T., Wassmann, R., 2017. How does burning of rice straw affect CH4 and N2O emissions? A comparative experiment of different on-field straw management practices. Agric. Ecosyst. Environ. 239, 143–153. https://doi.org/10.1016/j.agee.2016.12.042.
Roy, P., Kaur, M., Burman, R.R., Sharma, J.P., Roy, T.N., 2018. Determinants of paddy straw management decision of farmers in Punjab. J. Commun. Mobiliza. Sustain. Dev. 13 (2), 203–210.
Sahai, S., Sharma, C., Singh, D.P., Dixit, C.K., Singh, N., Sharma, P., Singh, K., Bhatt, S., Ghude, S., Gupta, V., Gupta, R.K., Tiwari, M.K., Garg, S.C., Mitra, A.P., Gupta, P.K., 2007. A study for development of emission factors for trace gases and carbonaceous particulate species from in situ burning of wheat straw in agricultural fields in India. Atmos. Environ. 41, 9173–9186. https://doi.org/10.1016/j.atmosenv.2007.07.054.
Sahai, S., Sharma, C., Singh, S.K., Gupta, P.K., 2011. Assessment of trace gases, carbon and nitrogen emissions from field burning of agricultural residues in India. Nutrient Cycl. Agroecosyst. 89, 143–157. https://doi.org/10.1007/s10705-010-9384-2.
Sen, A., Abdelmaksoud, A.S., Nazeer Ahammed, Y., Alghamdi, M.., Banerjee, T., Bhat, M.A., Chatterjee, A., Choudhuri, A.K., Das, T., Dhir, A., Dhyani, P.P., Gadi, R., Ghosh, S., Kumar, K., Khan, A.H., Khoder, M., Maharaj Kumari, K., Kuniyal, J.C., Kumar, M., Lakhani, A., Mahapatra, P.S., Naja, M., Pal, D., Pal, S., Rafiq, M., Romshoo, S.A., Rashid, I., Saikia, P., Shenoy, D.M., Sridhar, V., Verma, N., Vyas, B.M., Saxena, M., Sharma, A., Sharma, S.K., Mandal, T.K., 2017. Variations in particulate matter over Indo-Gangetic Plains and Indo-Himalayan Range during four field campaigns in winter monsoon and summer monsoon: role of pollution pathways. Atmos. Environ. 154, 200–224. https://doi.org/10.1016/j.atmosenv.2016.12.054.
Shafie, S.M., 2016. A review on paddy residue based power generation: energy, environment and economic perspective. Renew. Sustain. Energy Rev. 59, 1089–1100. https://doi.org/10.1016/j.rser.2016.01.038.
Sharma, K., Garg, V.K., 2018. Comparative analysis of vermicompost quality produced from rice straw and paper waste employing earthworm Eisenia fetida (Sav.). Bioresour. Technol. 250, 708–715.
Sidhu, H.S., Manpreet-Singh, Humphreys, E., Yadvinder-Singh, Balwinder-Singh, Dhillon, S.S., Blackwell, J., Bector, V., Malkeet-Singh, Sarbjeet-Singh, 2007. The Happy Seeder enables direct drilling of wheat into rice stubble. Aust. J. Exp. Agric. 47, 844.
Sidhu, H.S., Singh, M., Singh, Y., Blackwell, J., Lohan, S.K., Humphreys, E., Jat, M.L., Singh, V., Singh, S., 2015. Development and evaluation of the Turbo Happy Seeder for sowing wheat into heavy rice residues in NW India. Field Crop. Res. 184, 201–212. https://doi.org/10.1016/J.FCR.2015.07.025.
Singh, J., 2017. Management of the agricultural biomass on decentralized basis for producing sustainable power in India. J. Clean. Prod. 142, 3985–4000. https://doi.org/10.1016/j.jclepro.2016.10.056.
Singh, A., Sharma, S., 2002. Composting of a crop residue through treatment with

microorganisms and subsequent vermicomposting. Bioresour. Technol. 85, 107–111. https://doi.org/10.1016/S0960-8524(02)00095-0.
Singh, J., Panesar, B.S., Sharma, S.K., 2008. Energy potential through agricultural biomass using geographical information system-A case study of Punjab. Biomass Bioenergy 32, 301–307. https://doi.org/10.1016/j.biombioe.2007.10.003.
Song, K., Yang, J., Xue, Y., Lv, W., Zheng, X., Pan, J., 2016. Influence of tillage practices and straw incorporation on soil aggregates, organic carbon, and crop yields in a rice-wheat rotation system. Sci. Rep. 6, 36602.
Streets, D.G., Bond, T.C., Carmichael, G.R., Fernandes, S.D., Fu, Q., He, D., Klimont, Z., Nelson, S.M., Tsai, N.Y., Wang, M.Q., Woo, J.-H., Yarber, K.F., 2003a. An inventory of gaseous and primary aerosol emissions in Asia in the year 2000. J. Geophys. Res. Atmos. 108 https://doi.org/10.1029/2002JD003093.
Streets, D.G., Yarber, K.F., Woo, J.-H., Carmichael, G.R., 2003b. Biomass burning in Asia: annual and seasonal estimates and atmospheric emissions. Global Biogeochem. Cycles 17. https://doi.org/10.1029/2003GB002040 n/a-n/a.
Sun, J., Peng, H., Chen, J., Wang, X., Wei, M., Li, W., Yang, L., Zhang, Q., Wang, W., Mellouki, A., 2016. An estimation of CO2 emission via agricultural crop residue open field burning in China from 1996 to 2013. J. Clean. Prod. 112, 2625–2631. https://doi.org/10.1016/j.jclepro.2015.09.112.
Suthar, S., 2008. Bioconversion of post harvest crop residues and cattle shed manure into value-added products using earthworm Eudrilus eugeniae Kinberg. Ecol. Eng. 32, 206–214. https://doi.org/10.1016/J.ECOLENG.2007.11.002.
Tilman, D., Fargione, J., Wolff, B., D'Antonio, C., Dobson, A., Howarth, R., Schindler, D., Schlesinger, W.H., Simberloff, D., Swackhamer, D., 2001. Forecasting agriculturally driven global environmental change. Science (80-) 292.
United Nations, Department of Economic and Social Affairs, Population Division, 2015. World Population Prospects: The 2015 Revision, Key Findings and Advance Tables. Working Paper No. ESA/P/WP.241.
Venkataraman, C., Habib, G., Kadamba, D., Shrivastava, M., Leon, J.F., Crouzille, B., Boucher, O., Streets, D.G., 2006. Emissions from open biomass burning in India: integrating the inventory approach with high-resolution Moderate Resolution Imaging Spectroradiometer (MODIS) active-fire and land cover data. Global Biogeochem. Cycles 20, 1–12. https://doi.org/10.1029/2005GB002547.
Verheijen, F., Jeffery, S., Bastos, A.C., Van der Velde, M., Diafas, I., 2010. Biochar application to soils. A critical scientific review of effects on soil properties, processes, and functions. EUR 24099, 162.
Yang, S., He, H., Lu, S., Chen, D., Zhu, J., 2008. Quantification of crop residue burning in the field and its influence on ambient air quality in Suqian, China. Atmos. Environ. 42, 1961–1969. https://doi.org/10.1016/j.atmosenv.2007.12.007.
Yin, H., Zhao, W., Li, T., Cheng, X., Liu, Q., 2017. Balancing straw returning and chemical fertilizers in China: role of straw nutrient resources. Renew. Sustain. Energy Rev. 1–8. https://doi.org/10.1016/j.rser.2017.06.076.
Zeng, X., Ma, Y., Ma, L., 2007. Utilization of straw in biomass energy in China. Renew. Sustain. Energy Rev. 11 (5), 976–987.
Zhang, H., Hu, D., Chen, J., Ye, X., Wang, S.X., Hao, J.M., Wang, L., Zhang, R., An, Z., 2011. Particle size distribution and polycyclic aromatic hydrocarbons emissions from agricultural crop residue burning. Environ. Sci. Technol. 45, 5477–5482. https://doi.org/10.1021/es1037904.
Zhang, H., Hu, J., Qi, Y., Li, C., Chen, J., Wang, X., He, J., Wang, S., Hao, J., Zhang, L., 2017. Emission characterization, environmental impact, and control measure of PM 2.5 emitted from agricultural crop residue burning in China. J. Clean. Prod. 149, 629–635.
Zhang, X., Lu, Y., Wang, Q.G., Qian, X., 2018. A high-resolution inventory of air pollutant emissions from crop residue burning in China. Atmos. Chem. Phys. Discuss.